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AUDIO-MAGNETOTELLURIC SURVEYING AND ITS APPLICATION FOR THE CONCEALED OREBODIES PROSPECTING IN YUELE LEAD-ZINC DEPOSIT AREA, DAGUAN DISTRICT, NORTHEASTERN YUNNAN PROVINCE, CHINA

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ABSTRACT

The results of recent mineral exploration in the Yuele lead-zinc mining area of Daguan County, northeastern Yunnan province, showed that there are many areas with anticline outcrops of early Paleozoic strata under thick late Paleozoic strata in northeastern Yunnan province, where developed some hiddensalt structures (SSs), often led to lead-zinc polymetallic mineralization with varying degrees along the tension torsional fault (belts) or fracture (joint). These ore-bodies belong to the epigenetic hydrothermal filling vein-type deposit, often formed the industrial ore bodies, and the prospecting potential is great. In many places, the superficial mineralization information displayed clear, but the deep mineralization information is unknown, so the concealed ore-bodies prospecting is little. It is an advantage method for the audio-megnetotelluric (AMT) surveying to characterize the size, resistivity and skin depth of the polarizable mineral deposit concealed beneath thick overburden. To obtain more reliable results, we have measured electrical resistivity and polarization of the geological samples and the drilling samples for the subsequent data analysising. Based on the controlled known ore-bodies measurement testing, further studies will attempt to determine if induced polarization parameters extracted from the AMT surveying data can also be used to determine the size and resistivity of the mineralized area. This paper presents the surveying results using AMT method to evaluate the concealed lead-zinc mineralization in Yuele lead-zinc ore field, Daguan county, northeastern Yunnan province, China. After comparing the interpretation result of AMT surveying data with the geological data and the drilling data, it is found that there is some distinct difference in resistivity and polarizable between ore-bodies hosted stratum, upper stratum and gypsum stratum. The result shows that AMT method is helpful to identify lead-zinc mineralization under this geological condition.

KEYWORDS: Audio, Magnetotelluric Method (AMT), Physical Property Parameters, Concealed Ore, Bodies Predicting, Salt TECTONICS (SSs), Yuele Lead-Zinc Ore Field, Northeastern Yunnan Province

INTRODUCTION

Due to the complexity of geological conditions and mineralization, it is very difficult to obtain good results for the mineral prospecting researching only through the metallogenic laws. Currently, mineral prospecting methods based solely on geological theory haven't been met the requirements of modern mineral exploration (Wang et al., 2009; Xue et al., 2010, 2012). So that, it is necessary to arrange reasonably the prospecting projects, along with research and application the geophysical methods to predict the location of the concealed ore-bodies.

Along the metallogenic belt in northeastern Yunnan province that is important composition of the lead-zinc polymetallic mineralization area in Sichuan-Yunnan-Guizhou, there has found more than 130 lead-zinc deposits and mining areas with difference large and medium scale (Figure 1A). But in this region existthe minor axis anticline outcrop area with early Paleozoic strata and underlying very thick late Paleozoicstrata. And in the tension-torsional faulted and shattered zone or intersection of difference direction faults, it developed many lead-zinc polymetallic depositsor mineralizating points with difference poor and rich degree. At many areas, the mineralization bodies are relatively obvious on ground shallows, but it is very difficult and not clear for the prospecting potential in the depth, the prospecting progress is slow. The Yuelemining are abelong to the themetallogenic belt from Longjinggou-Hanjiapingzi to Gaoqiao-Shachiin Daguan District of Yunnan Province, it has great prospect for copper-lead-zinc mining prospecting. In recent years, the projects for prospecting evaluation and mineral geological observation in this areafound that the mineralization patterns and geological characteristics of the stratiform and steep dipping vein ore-bodies (Xue et al., 2010, 2012). Because the developing of the folds and faults in this area, geochemical observation has found some mineralization anomalies, but the vein shape ore-bodies have great variations, and the occurring of the salt tectonics in the depth, so the observation and prediction of the deep concealed ore-bodies have limitation.

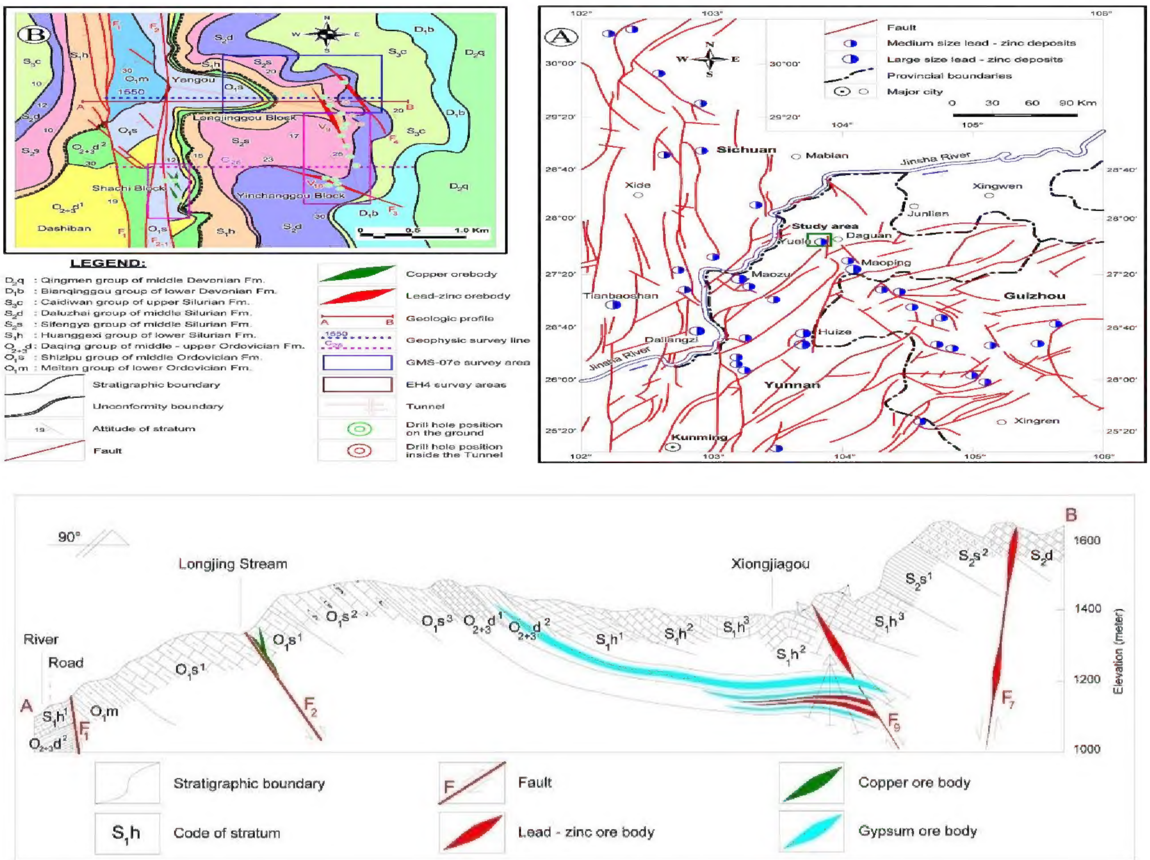

Figure 1: The Regional and Ore Field Geological Map of Yuele Lead-Zinc Deposit

A show the distribution of lead-zinc deposits in Sichuan-Yunnan-Guizhou border area (modified from Liu and Lin, 1999). B shows the structure outline map in Yuele lead-zinc deposit. The low Panel show the AB geological profile.

Therefore, this article took the lead-zinc deposit in the Yuele mining area as the object to study the metallogenic prospecting method. To help characterizing the size, electrical resistivity and skin depth of the polarizable mineral deposits concealed beneath thick overburden, so audio-megnetotelluric (AMT) method surveying(Abedi and Norouzi, 2012; An and

Di, 2007; Chen et al., 2009; Van Tuyen, 2011; Manzella and Zaja, 2006; Sampson and Rodriguez, 2010) was selected. To obtain an obviously result and more reliability, we have measured electrical resistivity and polarizable of the geological samples and the drilling samples for the AMT surveying data analysising. Further studies will attempt to determine if induced polarization parameters extracted from the AMT surveying data, also can be used to determine the size and electrical resistivity of the mineralized area.

GEOLOGICAL SETTING

Regional Geology

The Yuele lead-zinc mining area is belong to the northern part of the lead-zinc polymetallicmetallogenic belt in the northeastern Yunnan province (Figure 1A). Its special geological structural position and complex structural evolution history, has decisively influenced on the lead-zinc mineralization. The regional outcropped is made up of a suite of Paleozoicvolcanic rocks, terrigenousclastic rocks, and carbonate rock. The continuous outcrops include the Ordovician, Silurian and Devonian strata in this region, the total thickness is more than 3000 meters. And the copper, lead and zinc ore-bodies almost exist in the carbonate rocks in different strata (Table 1, Figure 1B). The mainly magma rocks are the amygdaloidal and vesiculate basalt of Emei Mount Formation of Upper Permian ($P_2\beta$), erupted in Late Hercynian and widely distributed in the regional area of Yangtze platformin southwestern China. The influence of magma in this formation on the lead-zinc mineralization surrounding the Yangtze platform, has many different disputes.

In the northeastern Yunnan region there are some main faults, including near SN trending Xiaojiang fault, NE trending Qiaojia-Lianfeng fault, NW trending Kangding-Daguan-Shuicheng fault, and SN trending Zhaotong-Qujing burial fault, and many developed secondary faults. In this region there lay some dome structures near SN trending Mohan-Qinglin belong to the northeastern section of Sayu River fold syncline eastern wing of Zhenxiong-Zhaotong fault, the main part position is secondary extensive wide and gently monoclinal structure of anticline eastern wing. The F_1 and F_2 thrust faults across anticline core is located in near SN trending, alternate NE NEE trending secondary folds, NW-NNW and NE-NNE trending faults and interlayer fracture zone, and formed the structure pattern with grid shape (Figure 1B).

Deposit Geology

The uncovering projects determined three types of copper, lead and zinc deposits in this mining area, the upper part are vein-type Pb-Zn (-Ag) ore-bodies and stratiform-type Cu-Pb-Ag ore-bodies, the under part is stratiform-type Pb-Zn (-Ag) ore-bodies. The main ore-bearing strata are limestone, carbonaceous debris argillaceous limestone, dolomitic limestone, calcite dolomite, and quartz sandstone in Ordovician and Silurian formation. Three types of ore-bodies exist together with similar geological features and obvious forming origin relationship. The known ore-bodies (ore mineralization bodies) are produced from in flanking plume-like fractures and steep dipping tension-torsional faults and fracture zones that is near SN trending and eastern plate of the F_2 fault. Order of faults and ore-bodies (mineralization bodies) can be arranged as follows, the F_2, F_3, F_4 and F_5 fault produced the V_{16} (Cu-Pb), V_{10} (Pb-Zn), V_8 (Pb-Zn) and V_9 (Pb-Zn) ore-body (mineralization body).

The forms of ore minerals are simply. The main ore minerals have galena, sphalerite, pyrite and little chalcocite, chalcopyrite. The main gangue minerals have calcite, dolomite, quartz, barite, gypsum and little fluorite. The main ores have layer, stratiform, vein, stockwork, and massive structure. Concretization is automorphic, hypautomorphic,

xenomorphic, metasomatic corrosion and metasomatic relict. In this mining area, the copper, lead and zinc ore-bodies are vein-type deposit, filled on epigenetic by low temperature hydrothermal, controlled by salt tectonics related to thrust fold. Salt-related structures are spatial-temporal relationship well with copper, lead and zinc polymetallic mineralization.

Table 1: The Stratum Characteristics Profiles in Yuele Lead-Zinc Ore Field

Age		Formation	Code	Lithology	Ore bodies	Stratum features	Thickness (meter)
Paleozoic	Devonian	Qingmen	D_2q			Argillaceous siltstone, argillite bedded with marls	38 - 72
		Bianqinggou	D_1b			Calcilutite	0 - 120
	Silurian	Caidiwan	S_3c^3			Argillite bedded fine grain quartz sandstone	100
			S_3c^2			Argillaceous limestone, silty argillite	
			S_3c^1			Carbonaceous graptolite shale	
		Daluzhai	S_2d^3		Pb Zn Ag	Fine grained limestone	91.6
			S_2d^2			Calcite dolomite with shale strip limestone	
			S_2d^1			Carbonaceous silty mudstone interblending with bioclastic limestone	
		Sifengya	S_2s^2			Fine and medium grained feldspar quartz sandstone	176.3
			S_2s^1			Carbonaceous silty mudstone with siltstone	
		Huanggexi	S_1h^3		Pb Zn Ag	Carbon calcarenite	> 300
			S_1h^2			Fine grained limestone bedded with dolomitic limestone	
			S_1h^1			Carbonaceous argillaceous limestone	
	Ordovician	Daqing	$O_{2+3}d^2$		Gypsum	Silty mudstone and gypsum-bearing siltstone	118.8
			$O_{2+3}d^1$			Dolomite bedded with limestone	
		Shizipu	O_1s^3		Pb Zn Ag Cu Pb	Mudstone bedded with marls	> 250
			O_1s^2			Fine grained calcite dolomite	
			O_1s^1			Limestone with argillite	
		Meitan	O_1m			Argillite and silty shale	171.1

STUDY METHOD

Electrical Properties of Rocks

Electromagnetic geophysical methods detect variations in the electrical properties of rock units, in particular electrical resistivity in units of ohm-meters (Ω·m), or its inverse, electrical conductivity in units of Siemens/meter (S/m). Electrical resistivity can be correlated with geological units on the surface and at depth by using lithologic logs to provide a three-dimensional picture of subsurface geology. In the upper crust, the resistivities of geological units are largely depend upon their fluid content, pore-volume porosity, interconnected fracture porosity, and the presence of conductive minerals, such as clay, graphitic carbon, and metallic minerals.

The measuring results are list in Table 2, the samples of lead-zinc ore, siltstone, limestone containing barite veins, carbonaceous argillaceous limestone, argillaceous limestone and limestone containing calcite veins are high polarizable, polarizable (M1) geometric average value is more than 2%. Siltstone containing calcite veins, argillaceous siltstone and argillaceous limestone containing bedding calcite veins, argillaceous limestone (mineralization zone) and finely crystalline limestone are low polarizable, M1 geometric average value is less than 2%.

Siltstone containing calcite veins, argillaceous siltstone, bedding calcite argillaceous limestone and finely crystalline limestone have apparent resistivity geometric average less than 1000 ohm-meters (Ω·m). Lead-zinc ore, siltstone, limestone containing barite veins, carbonaceous argillaceous limestone, argillaceous limestone, argillaceous limestone (mineralization zone) and limestone specimens containing calcite veins have the electrical resistivity more than 1000 (Ω·m). In which, argillaceous limestone (mineralization zone) and limestone specimens containing calcite veins have apparent resistivity more than 7000 (Ω·m).

Table 2: Electrical Properties of All Kinds of Rocksin Yuele Lead-Zinc Ore Field

Name of Rock	Polarizable-M1(%)			Electrical Resistivity-ρ(Ω·m)		
	Max Value	Min Value	Geometric Average Value	Max Value	Min Value	Geometric Average Value
Limestone containing calcite veins	3.1	1.2	2.1	37120	3710	8391
Argillaceous limestone	3.7	2.1	2.9	4853	1285	2886
Finely crystalline limestone	1.3	0.3	0.7	1235	766	913
Carbonaceous argillaceous limestone	3.8	0.5	2.1	5815	518	2262
Limestone containing barite veins	3.0	2.1	2.5	6013	2794	4290
Argillaceous limestone (mineralization zone)	4.4	0.4	1.1	99259	842	7092
Argillaceous limestone containing bedding calcite veins	1.2	0.5	0.8	603	534	567
Argillaceous siltstone	1.6	0.4	0.7	1167	282	542
Siltstone	4.2	2.3	3.1	3697	483	1336
Siltstone containing calcite veins	4.4	0.3	1.9	1562	254	518
Lead – zinc ore	2.4	20.0	11.5	10	192	25
Pyrite lead – zinc ore	0.4	24.0	6.3	6	7481	210
limestone	0.4	4.9	1.3	541	211698	13816
Dolomite	0.3	2.9	0.9	197	135253	12024
Sandstone	2.9	2.9	2.9	2684	2684	2684

In short, lead-zinc ore, siltstone, siltstone containing barite veins, carbonaceous argillaceous limestone, argillaceous limestone and limestone containing calcite veins often have high polarizable characteristics and high electrical resistivity characteristics. Siltstone containing calcite veins, argillaceous siltstone, bedding calcite argillaceous limestone and finely crystalline limestone often have low polarizable characteristics and low electrical resistivity characteristics. Argillaceous limestone (mineralization zone) often has low polarizable features and high electrical resistivity features.

About AMT Method

AMT measures the electric (E) and magnetic (H) components of the electromagnetic field (Hermance et al., 1976). The E-field is sensed as a voltage across a grounded wire, while the H-field is sensed as a voltage in a high-gain magnetic antenna. Based on electromagnetic theory and Maxwell Equation, three components of E and H could be calculated, and then the ratio of horizontal perpendicular components, E_x and H_y, gives the Cagniard resistivity (Cagniard, 1953) of the ground with the coordination in Figure 2.

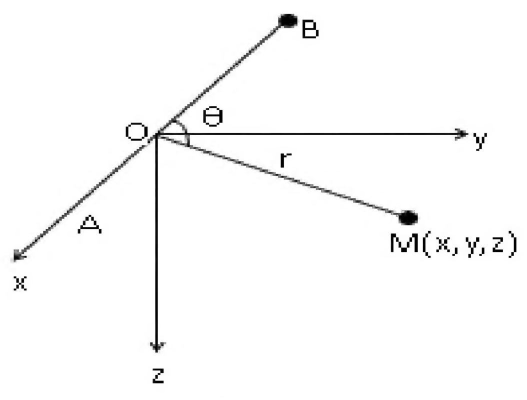

Figure 2: Horizontal Dipole and Coordinate Geometry

In the Figure 2, θ is the angle of AB and M point, O is the center of AB, r is the distance of AB and M, μ_0 is permeability.

$$E_x = \frac{I.AB.\rho_1}{2\pi r^3}.(3\cos^2\theta - 2) \tag{1}$$

$$E_y = \frac{3.I.AB.\rho_1}{4\pi r^3}.\sin 2\theta \tag{2}$$

$$E_z = (i-1)\frac{I.AB.\rho_1}{2\pi r^2}.\sqrt{\frac{\mu_0\omega}{2\rho_1}}.\cos\theta \tag{3}$$

$$H_x = -(1+i)\frac{3I.AB}{4\pi r^3}.\sqrt{\frac{2\rho_1}{\mu_0\omega}}.\cos\theta.\sin\theta \tag{4}$$

$$H_y = (1+i)\frac{I.AB}{4\pi r^3}.\sqrt{\frac{2\rho_1}{\mu_0\omega}}.(3\cos^2\theta - 2) \tag{5}$$

$$H_z = i\,\frac{3I.AB.\rho_1}{2\pi\mu_0\omega r^4}.\sin\theta \tag{6}$$

the ratio of E_x and H_y:

$$\frac{E_x}{H_y} = \frac{\frac{I.AB.\rho_1}{2\pi r^3}.(3\cos^2\theta-2)}{(1+i)\frac{I.AB}{4\pi r^3}.\sqrt{\frac{2\rho_1}{\mu_0\omega}}.(3\cos^2\theta-2)} = \frac{2\rho_1}{(1+i)\sqrt{\frac{2\rho_1}{\mu_0\omega}}} \tag{7}$$

in brief:

$$\rho_s = \frac{1}{\mu_0\omega}\left|\frac{E_x}{H_y}\right|^2 \tag{8}$$

and then Cagniard resistivity is:

$$\rho_s = \frac{1}{5f}\frac{|E_x|^2}{|H_y|^2} \qquad (\rho \text{ in ohm-m}) \tag{9}$$

Their phases yield another quantity known as phase difference or impedance phase:

$$P = E_{Phare} - H_{Phare} \qquad (\text{P in milliradian}) \tag{10}$$

The depth of AMT data is related to signal frequency f and to resistivity ρ:

$$D = 502\sqrt{\frac{\rho}{f}} \qquad (\text{D in meters}) \tag{11}$$

From equation (11), the depth (D) depends on resistivity (ρ) and frequency (f), the survey is made in the corresponding frequency band to the underground research depth. General speaking, the high frequency data reflects the shallow geological body electrical characteristics and the lower frequency data reflects the deep geological body electrical characteristics.

Geophysical Surveying

Two geophysical surveys had been donein the Yuelemining area, and two different geophysical instrumentsof EH4 instrument and GMS-07e instrument are used. Both of the instruments are audio-magnetotelluric sounding (Figure 1B).

The EH4 instrument has been surveyed in April 2011, sum of survey line are 13 lines, sum of survey station are 226 stations, sum of survey line’s length are 7580 m. The distance between two adjacent survey stations is 30 m. And the

GMS-07e instrument thas been surveyed in December 2012, sum of survey line are 5 lines, sum of survey station are 224 stations, sum of survey line's length are 7200 m. The distance between two adjacent survey stations is 30 m.

Analytical Methods

Analytical Methods

The software used to analysis ATM surveying data is the software Mapros.

- Using the fast Fourier transform algorithm (FFT) to obtain the corresponding spectrum for the collected data, that is the corresponding relation between the frequency and amplitude in electric field or magnetic field.
- Using the impedance equation to obtain the corresponding relation between the Cagniard resistivity and frequency.
- Using the software MTPioneer to display the two-dimensional electrical resistivity inversion profile from the collected data, fitting the collected data and establishment model.
- Colligate the one-dimensional inversion and two-dimensional inversion to obtain the inversion finally.

The collected data after passing these processes, get the resistivity inversion section of each survey line. Combined with the geological data, drilling and other data to inference and interpretation.

INFERENCE AND INTERPRETATIONRESULTS

The analysis of 2D electrical resistivity inversion profile of the AMT method, combination of known geological data and borehole data, bring into comparisons with strata and structure of electrical resistivity inversion profile has been shown. Analysis of all the electrical resistivity inversion profiles to anomaly division of geophysical exploration and interpretation of geophysical exploration inversion profiles. Because of mine for low temperature hydrothermal vein type deposit, the ore mainly belong to epigenetic mineralization product filling, ore-body is significantly affected by the fracture zone and the ore-bearing strata combined. According to the borehole data have known obtainable orebody output area mostly associated with carbonaceous mudstone, limestone and that is corresponding to low electrical resistivity site of sounding inversion profile.

Therefore, when anomaly body divided according to the reflection of sounding electrical resistivity profile, combined with geological data and borehole data to inference and after that comprehensive analysis was carried out to determination (Figure 3, Figure 4).

CONCLUSIONS

- The interpretation results of the AMT method has identified the location of geological structure, deformation forms, and their spatial occurrence and depth variation.
- Comparing the interpretation results of the AMT method with the known borehole data, it is show that the location of medium electrical resistivity anomalies is the location of lead and zinc mineralization, the value of medium electrical resistivity anomalies is about 1000 ~ 3000 ($\Omega\cdot$m).

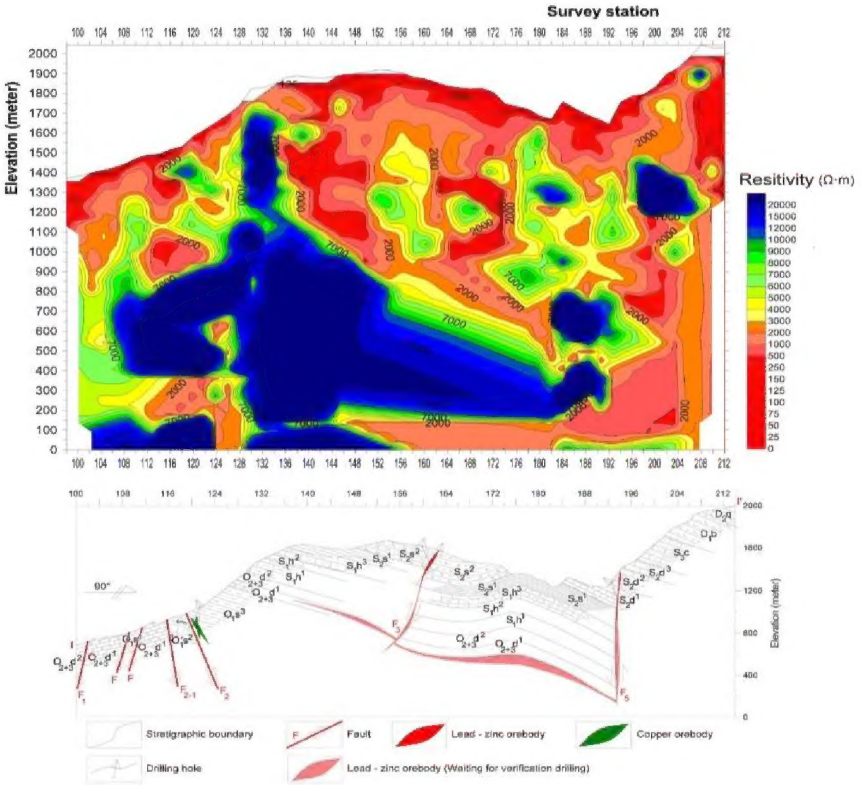

Figure 3: The Electrical Resistivity 2D Inversion Profile of Line C25 and its Geological Interpretation, the Survey Line Position is I-I' Line in Figure 1B

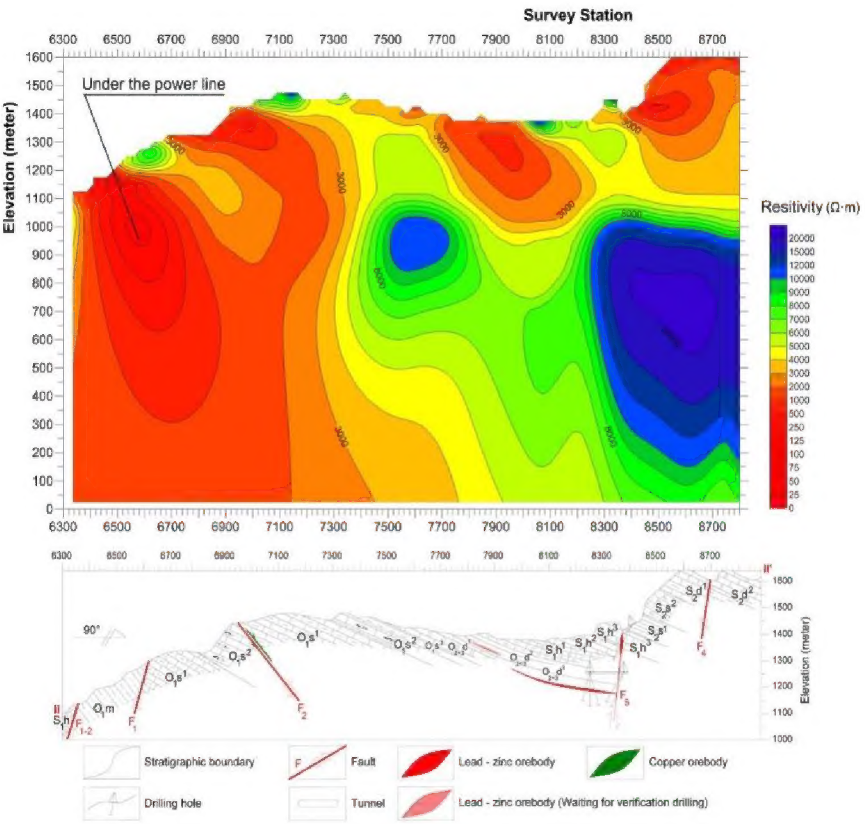

Figure 4: The Electrical Resistivity 2D Inversion Profile of Line 1550 and its Geological Interpretation, the Survey Line Position is II-II' Line 1550 in Figure 1B

- Based on the interpretation results of the AMT method, combined with the geological conditions and the known borehole data, the anomalies area can be designed as the drill verification to carry out the mineral predicting.

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